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Life cycle assessment of solar PV based electricity generation systems: A review

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ABSTRACT

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products viz. goods, services, etc. This paper presents a review of life cycle assessment (LCA) of solar PV based electricity generation systems. Mass and energy flow over the complete production process starting from silica extraction to the final panel assembling has been considered. Life cycle assessment of amorphous, mono-crystalline, poly-crystalline and most advanced and consolidate technologies for the solar panel production has been studied.

Contents

1. Introduction

In these last decades, energy related problems are becoming more and more important and involves the rational use of resources, the environmental impact due to the emission of pollutants and the consumption of non-renewable resources [1]. With regard to energy systems, many projects aimed at the mitigation of these problems are being planned, also to fulfil the more and more restrictive environmental laws. Many countries have introduced policy to promote the installation of new renewable source plants in order to reach the Kyoto protocol targets, and often a specific mention to photovoltaic plants is reported [2,3].

Life cycle assessment (LCA) is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product's life [4]. LCA stage includes definition of goal and scope, inventory analysis, impact assessment and interpretation of results as shown in Fig. 1 [5–7]. The goal and

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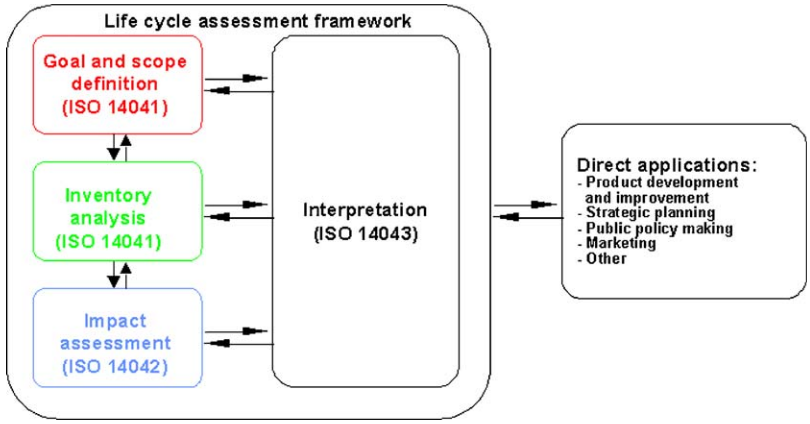

Fig. 1. Life cycle assessment framework [8].

scope definition describes the underlying question (objective), the system, its boundaries and the definition of a functional unit. The flows of pollutants, materials, resources are recorded in inventory analysis. These elementary flows (emissions, resource consumption, etc.) are characterize and aggregated for different environmental problems in impact assessment and finally conclusions are drawn in interpretation stage. LCA applications are comparisons of different product and systems, or different materials production or recycling methods. LCA can be used as a tool to detect potential for improvements with the aim to reduce impact on human health, environment and resource depletion.

Solar photovoltaic (PV) module converts solar energy directly into electricity and bring about environmental benefits such as greenhouse gas (GHG) and pollution reduction [9]. The PV industry has grown with an estimated 1.5 GW installed in year 2005. Most of this growth has come from European countries especially Germany and having grid-connected systems which was initially in the year 1990 were stand alone type [10]. The solar energy, which seems to be completely clean having no environmental impact but actually these systems also, emits greenhouse gases (GHG) emissions. In this paper a review has been done to estimate the environmental impacts of different solar PV based electricity generation systems using life cycle assessment technique.

2. Steps for fabrication of PV module

Silicon solar cells are perhaps the simplest and most widely used for space and terrestrial applications. The procedure for fabrication of mono-crystalline silicon solar PV module has been discussed in brief.

2.1. Purification of silicon

The silicon dioxide (SiO_2) is reduced to silica (Si) with carbon (C) in a large arc furnace. Further silicon is purified in the furnace by repeatedly pouring it and blowing with oxygen/chlorine mixture and finally solidifying it. This metallurgical grade is further purified for use in semi-conductor form. There are many different method exist to obtain solar-grade silicon (sog-Si). The most preferred one is the Siemens process in which metallurgical grade silicon is converted into a volatile compound which is condensed and then refined by fractional distillation.

2.2. Methods of growing silicon

There are several methods of growing single crystals of silicon from liquid, gas or solution such as: Czochralski technique, heat exchange method, dentritic web method, silicon on ceramic method, etc. [11].

2.3. Silicon wafers to silicon solar cells

The fabrication of solar cells from the single crystal silicon wafer involves many steps such as: surface preparation, dopants diffusion or junction formation, coating, etc. [12].

2.4. Module design

The individual cells are interconnected in series and parallel pattern for module fabrication. One module contains about 20–40 cells and each module may have three to five column of cells in series in such a way to get the desired output electrical characteristics. Since generally circular cells are produced but the packing density is not very high and about 15–20% of the module area remains uncovered. In case of square or hexagonal shaped cells better packing densities are obtained.

3. LCA of PV system

Photovoltaic (PV) technology is expected to be a leading technology to solve the issues concerning the energy and the global environment due to several advantages of the PV system.

3.1. LCA of amorphous PV systems

Schaefer and Hagedorn [13] carried out a comparative analysis of the surface and material requirements of different power stations. The accumulated energy consumption in the manufacturing and construction of PV electricity generation plants, CO_2 emissions caused by PV power generation and the energy amortization time or energy pay-back time (EPBT) were evaluated. The accumulated primary energy consumption for the construction of the photovoltaic power plants ranges from 13,000 to 21,000 kWh/kWp and represents the lowest threshold for the current state of the art. The life cycle CO_2 emission is 3.360 kg-CO_2/kWp for amorphous technology.

Alsema [14] studied the energy requirements and CO_2 emissions for the production of PV modules and BOS components of grid-connected PV systems. Thin film (amorphous) module and mono-crystalline (mc) silicon technologies were investigated and the energy pay-back period was found to be 2.5–3 years for rooftop installation and 3–4 years for multi-megawatt ground mounted system. The CO_2 emissions of the rooftop system were calculated as 50–60 g/kWh$_e$ now and probably 20–30 g/kWh$_e$ in the future.

Table 1
LCA of amorphous solar PV system.

S. no.	Year	Location	Efficiency (%)	Power rating	Life time (years)	EPBT (years)	GHG emissions (g-CO_2/kWh$_e$)
1.	1996 [18]	Netherlands	10	30 m^2 [a]	20	na	47.0
2.	2000 [14]	Netherlands	7.0	na	30	2.7	50.0
3.	2002 [19]	US	5.7	8 kW	30	na	39.0
4.	2007 [15]	US	6.3	33 kW	20	3.2	34.3
5.	2008 [17]	China	6.9	100 MW	30	2.5	15.6

[a] 30 m^2 is the area of solar PV system.

Pacca et al. [15] studied the LCA of PVL62 (photovoltaic laminates) and PVL136 thin film (amorphous) modules including BOS, inverter installations and transportation were modelled using the life cycle software Simapro 6.0. Material and energy inputs were obtained from the manufacturer [16]. The manufacturing of one PVL136 module consumes 371 MJ of primary energy in materials and 1490 MJ of primary energy as process energy. The life CO_2 emissions were 34.3 g-CO_{2eq}/kWh$_e$.

Ito et al. [17] has studied the cost and life cycle analysis for 100 MW very large scale PV (VLS-PV) systems at Gobi desert using amorphous silicon (a-si) solar cell modules. The life cycle CO_2 emissions are 15.6 and 16.5 g-CO_{2eq}/kWh$_e$ considering temperature of the desert 5.8 and 30.2 °C, respectively. Table 1 shows LCA of amorphous solar PV systems.

3.2. Mono-crystalline (mc) PV systems

Schaefer and Hagedorn [13] carried out a comparative analysis of the surface and material requirements of different power stations. The accumulated energy consumption in the manufacturing and construction of PV electricity generation plants, CO_2 emissions caused by PV power generation and the energy amortization time or energy pay-back time (EPBT) were evaluated. The life cycle CO_2 emission is 5.020 kg-CO_2/kWp for mono-crystalline (mc) silicon technology.

Prakash and Bansal [20] has carried out energy analysis of solar PV module production in India. Mono-crystalline (mc) wafers of p-type silicon were imported for cell and module production in India. The energy pay-back period of a mono-crystalline SPV module in India was evaluated as approximately 4 years.

Kato et al. [21] have done a life cycle analysis of single-crystalline (mc) silicon photovoltaic cells for a 3 kW residential PV system installed on the rooftop using off-grade silicon supplied from semi-conductor industries. Annual electrical output of the PV system is calculated at 3.47 MWh/year. Balance of system (BOS) of the residential PV system consists of supporting structure and an inverter. The indirect CO_2 emissions of the PV systems made up of off-grade silicon was estimated 91 g-CO_{2eq}/kWh$_e$.

Kannan et al. [22] performed LCA and life cycle cost analysis for a distributed 2.7 kWp solar PV system operating in Singapore. In this study EPBT analysis of the solar PV system, their GHG emission has been estimated. The 2.7 kWp solar PV systems consists of 36 mono-crystalline (mc) silicon modules (12 V, 75 Wp) mounted on a building rooftop with aluminium supporting structures and concrete blocks for the base. All indicators of the study such as energy use, emissions and cost are indexed based on the functional unit which is defined as 1 kWh of AC electricity. The life cycle energy use would reduce to 2.2 MJ/kWh$_e$ and the EPBT would be 4.5 years. The GHG emissions would be about 165 g- CO_2/kWh$_e$.

Mathur et al. [23] estimated energy yield ratio (EYR) and cumulative energy demand (CED) for single-crystalline (mc) silicon PV module having peak output of 35 W and having efficiency of 13%. The EYR comes in the range from 1.65 to 2.6 for Indian context.

Kreith et al. [24] has studied 300 kW PV plant at Austin working since 1986. The plant consists on a 3.5 acre field of 2620 m^2 and having single crystal (mc) silicon cell. The cells are mounted on 42 single axis passive trackers that rotate around a north–south, horizontal axis. The total embodied energy and CO_2 production (emission) for 300 kW PV plant were 16.5 GWh and 4205 metric tons of CO_2. The life cycle CO_2 emissions are 280 g-CO_{2eq}/kWh$_e$.

Muneer et al. [25] has carried out energetic, environmental and monetary LCA of photovoltaic installation at Napier University's Merchiston campus. This PV installation consists of 32 rows of BP solar silicon panels covering a total nominal area of 160 m^2 and maximum generation of 14.4 kWp (kW peak) alternating current (AC) power. This power is generated from the BP solar high efficiency mono-crystalline panels (mc-si) each of which produces 90 W of power at 22 V [26]. It was found that an average of just less than 11,000 kWh$_e$ AC output would be generated annually. The EPBT for this installation is estimated to be 8 years and life cycle GHG emissions are 44 g-CO_{2eq}/kWh$_e$. Table 2 shows LCA of mono-crystalline solar PV systems.

3.3. Poly-crystalline (pc) PV systems

Battisti and Corrado [27] have done LCA of a conventional multi-crystalline (pc) silicon PV system which is grid-connected and retrofitted on a tilted roof in Rome. The calculated EPBT and CO_2 PBT were 3.3 and 4.1 years, respectively.

Tripanagnostopoules et al. [28] carried out an LCA study on PV and PV/T system using SimaPro 5.1 software determining two pay-back time parameters for a 3 kWp PV or PV/T system with an active surface of 30 m^2 with multi-crystalline (pc) silicon PV modules. The energy pay-back time (EPBT) and the CO_2 pay-back time (CO_2 PBT). The best case is PV/T with glazing (with or without reflectors)

Table 2
LCA of mono-crystalline (mc) solar PV system.

S. no.	Year	Location	Efficiency (%)	Power rating	Life time (years)	EPBT (years)	GHG emissions (g-CO_2/kWh$_e$)
1.	1990 [24]	US	8.5	300 kW	30	na	280
2.	1997 [21]	Japan	na	3 kW	20	15.5	91
3.	2000 [13]	Netherlands	14.0	na	30	3.2	60.0
4.	2002 [23]	India	13.0	35 W	20	na	64.8
5.	2006 [25]	UK	11.5	14.4 kW	30	8	44.0
6.	2006 [22]	Singapore	7.3–8.9	2.7 kW	25	5.87	217
7.	2006 [22]	Singapore	10.6	2.7 kW	25	4.47	165

Table 3
LCA of poly-crystalline (pc) solar PV system.

S. no.	Year	Location	Efficiency (%)	Power rating	Life time (years)	EPBT (years)	GHG emissions (g-CO_2/kWh$_e$)
1.	2003 [34]	China	12.8	100 MW	30	1.7	12.0
2.	2005 [36]	Japan	10.0	3 kW	30	na	53.4
3.	2005 [27]	Italy	10.7	1 kW	20[a]	3.3	26.4
4.	2005 [28]	Greece	na	3 kW	20[a]	2.9	104
5.	2007 [15]	US	12.92	33 kW	20	5.7	72.4
6.	2008 [17]	China	12.8	100 MW	30	1.9	12.1
7.	2008 [17]	China	15.8[b]	100 MW	30	1.5	9.4

[a] By considering 20 years life time.
[b] High efficiency (pc) solar cell.

operating at the lowest temperature (25 °C) shows pay-back period of 0.8 years.

Mason et al. [29] has studied LCA of the energy requirements and GHG emissions of the balance of systems (BOS) of components of the 3.5 MWp multi-crystalline (pc-si) PV installation at Tuscon Electric Power (TEP) Springerville, AZ field plant. TEP provided an itemized BOS bill of materials for their pc-si PV installations. The life expectancy of the PV metal support structures is assumed to be 60 years, inverters and transformers are considered to have life of 30 years. The boundaries of the life cycle energy and GHG emissions analysis includes from material production to product end of life disposal. The life cycle energy uses and GHG emissions over the complete life cycle of PV BOS were determined from the commercial life cycle inventory (LCI) databases, Franklin [30], Ecoinvent [31] and public domain sources from NREL [32] and Aluminium Association [33]. The total primary energy for the BOS life cycle was estimated to be only 526–542 MJ/m^2 by using different databases. The EPBT is 0.21 year and the GHG emissions during the life cycle of the BOS were 29–31 kg CO_{2eq}/m^2.

Pacca et al. [15] studied the LCA of KC120 multi-crystalline modules including BOS, inverter installations and transportation were modelled using the life cycle software Simapro 6.0. The manufacturing of one KC120 module consumes 1000 MJ of primary energy in materials and 3020 MJ of primary energy as process energy. The net energy ratio (NER) and EPBT for KC120 were 2.7 and 7.5, respectively. The life CO_2 emissions were 72.4 g-CO_{2eq}/kWh$_e$ for assuming US conditions whereas 54.6 g-CO_{2eq}/kWh$_e$ by considering European conditions.

Ito et al. [34] studied very large scale multi-crystalline (pc) PV system of 100 MW which would be installed at Gobi desert. The EPBT and life cycle CO_2 emission has been estimated for three types of PV module arrangement, i.e. wide model, moderate model and tall model. The EPBT and life cycle CO_2 emission were <2 years and 12 g-CO_{2eq}/kWh$_e$ for tilt angle 20° and for wide model.

Komiyama et al. [35] has studied CO_2 pay-back time for multi-crystalline (pc) silicon for three different cases. These cases were Japanese made solar cells were installed in a power station constructed in Indonesia, Japanese made solar cells were installed in Japan and Indonesian made solar cells were installed in Indonesia. Their respective CO_2 pay-back times were 3.37, 8.04 and 3.91.

Hondo [36] has studied the GHG emission of rooftop type PV systems for both base and future cases. The base case assumed that PV cells use solar-grade poly-crystalline (pc) silicon. The assumed cell and system efficiencies are 17 and 10%. Future case 1 assumed that PV cells use the same SOG poly-crystalline silicon as the base case and the production rate of PV cells was 1 GW/year. Future case 2 assumed that SOG amorphous silicon was used with system efficiency of 8.6% and the production rate was 1 GW/year. The results were 53.4, 43.9 and 26 for base and future cases, respectively.

Ito et al. [17] has studied the cost and life cycle analysis for 100 MW very large scale PV (VLS-PV) system at Gobi desert using poly-crystalline silicon (pc-si) solar cell modules. The life cycle CO_2 emissions are 15.6 and 16.5 g-CO_{2eq}/kWh$_e$ considering temperature of the desert 5.8 and 30.2 °C, respectively.

Jungbluth [37,38] has studied 12 different grid-connected PV systems. Out of those 12 systems, 10 different small scale plants of 3 kWp capacity and installed in the year 2000 and two slanted roof plants based on a scenario with a future production technology. GHG emission for PV ranges from 39 to 110 g-CO_{2eq}/kWh$_e$ with an average for the Swiss mix of 79 g-CO_{2eq}/kWh$_e$. The EPBT lies in the range of 3–6 years. Table 3 shows LCA of poly-crystalline solar PV systems.

3.4. Other PV systems

Greijer et al. [39] estimated life cycle GHG emissions of nano-crystalline dye sensitized (ncDSC) system by estimating an average life time of 5–30 years. The life cycle GHG emissions were in the range of 19–47 g-CO_{2eq}/kWh$_e$ for considering 20 years life time and estimated in the range of 78–188 g-CO_{2eq}/kWh$_e$ for 5 years life time. Even if the ncDSC system will last for such a short life time, the infrastructure for the solar cell (framing, electric connection, etc.) could be used over again with a new ncDSC panel which lower the impact.

Ito et al. [17] has studied the cost and life cycle analysis for 100 MW very large scale PV (VLS-PV) system at Gobi desert using CdTe and CIS solar cell modules. The life cycle CO_2 emissions are 15.6 and 16.5 g-CO_{2eq}/kWh$_e$ considering temperature of the desert 5.8 and 30.2 °C, respectively.

4. Discussions

The commonly used three types of solar PV system and some advanced solar cell had been discussed based upon life cycle assessment. The energy requirement and GHG emissions have been estimated for amorphous, mono-crystalline, poly-crystalline and other material based solar cells. Thin film modules (amorphous) solar cells consume less primary energy (embodied energy) as compared to other type of solar cells but the efficiency of these cells had also been lower as compared to other cells.

The variation in the EPBT and GHG emissions has been dependent upon many factors, such as the type of solar cell, solar panel orientation and angle, irradiation of the location, difference in installation (integrated or non-integrated systems as well as facade, flat roof and solar roof tiles), efficiency of the BOS components, size (capacity) of the system, lifetime of the system and the electricity mix of that particular country and year of study.

The EPBT for amorphous, mono-crystalline and poly-crystalline solar PV systems have been estimated in the order of 2.5–3.2, 3.2–15.5 and 1.5–5.7, respectively. Similarly GHG emissions are 15.6–50, 44–280 and 9.4–104, respectively.

5. Conclusions

The PV system is promising source of electricity generation for energy resource saving and CO_2 emission reduction, even if current technologies are applied. Further the development in efficiency of solar cells, amount of material used in the solar cell system and the system are designed for maximum use of recycled material will reduce the energy requirement and GHG emissions.

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